Physical Environment

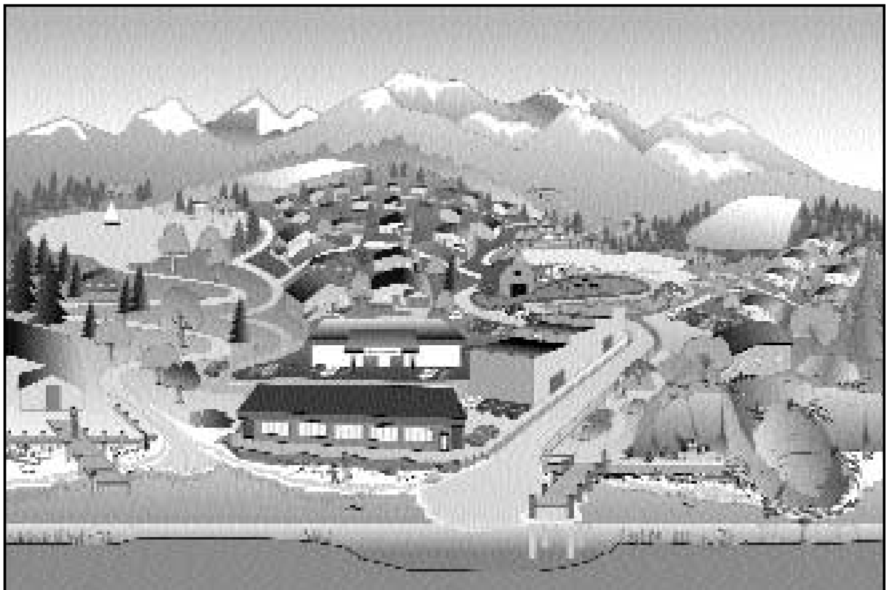
Summary

The physical character of the Puget Sound environment–including its landforms, currents and climate–determine the fundamental character of the Puget Sound ecosystem. The meteorological, hydrologic and geologic processes that form and maintain our rivers and streams, our marine waters and our shorelines provide the essential foundation for the chemical and biological elements of the Puget Sound ecosystem. Many human activities negatively affect Puget Sound's physical environment by altering its natural state. Dynamic changes in the Sound's physical environment also occur in response to winds, rain, currents and geologic processes.

Water delivered to the Puget Sound basin as rain and snow percolates through and runs off the land, gathering in streams, rivers and underground aquifers. This flow of water toward the Sound and the circulation of water within the Sound are the primary vehicles by which sediments, nutrients and woody debris are carried through the environment to support the various components of the Puget Sound ecosystem. Many organisms (e.g., crab and clam larvae and algae) also rely on the flow of water to carry them to, within and beyond Puget Sound. These same processes can transport contaminants to, within and beyond the Puget Sound ecosystem.

The character of the land, river and stream channels, floodways and shorelines of the Puget Sound basin affect the delivery and movement of water, sediments, nutrients, woody debris and contaminants in Puget Sound's watersheds. Figure 3 shows some of the human activities that alter the physical environment of Puget Sound by changing the character of the land, river and stream channels and shorelines.

Figure 3. Physical alterations to the Puget Sound environment.



Source: Visual Communication and EIS Unit, King County Department of Natural Resources.

Examples of effects from these alterations include:

- Development of river, lake and Puget Sound shorelines in the form of residential properties, industrial areas and commercial complexes can affect the delivery of water, sediments, nutrients and contaminants into the adjacent water.
- Development of urban, suburban and rural properties and the associated increase in impervious surfaces (surfaces such as roads, driveways, parking lots and lawns, that cannot be easily penetrated by water) causes increased surface runoff of stormwater. This increased flow can lead to scouring and other alteration of in-water environments.
- Nutrients (e.g., from fertilizers or fecal matter from pets) and contaminants (e.g., toxic chemicals from cars) are often highly concentrated on urban, suburban and rural lands. This can lead to high levels of contamination in stormwater runoff.
- Channelizing streams, filling wetlands and floodplains, and cutting forests adjacent to streams can disrupt the process of water, sediment, nutrient and debris delivery to Puget Sound.
- "Hardening" shorelines with bulkheads, as well as dredging and filling tidal and river delta areas, can alter water circulation and sediment transport processes along shorelines and in estuaries.

Other aspects of Puget Sound's physical environment—such as its climate and geology—*appear* to be beyond the direct influence of humans, but may, in fact, be affected by local or global human activities:

- Temperature, precipitation and other aspects of climate in the Puget Sound region reflect local variations over days, weeks and months. Larger patterns, including El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) affect climate change over years, decades and beyond. ENSO and the PDO are natural cycles, each characterized by shifts between cold, wet weather and warm, dry weather. ENSO operates over the time span of a year, while the PDO appears to span about a 20-year period. ENSO's two extreme conditions, El Niño and La Niña, primarily affect the region's winter weather (warm, dry weather versus cold, wet conditions, respectively). A warm-dry PDO regime appears to be ending; some atmospheric scientists think we already may have shifted to a cold-wet regime. On a global scale, air temperatures have increased through the 20th century. Rising temperatures may be caused by increases in the atmospheric concentration of carbon dioxide (and other greenhouse gases) in response to fossil fuel consumption and deforestation.

- The Puget Sound basin is geologically young and active. Steep slopes slide and bluffs recede as glacial features "mature." Earthquakes and volcanic events can quickly reshape the landscape. These processes will occur without (and in spite of) human intervention, but human development of unstable areas may lead to larger or more rapid changes in the landscape.

Findings

This section presents recent ocean and weather conditions and recent results from relevant studies of the Puget Sound Ambient Monitoring Program (PSAMP). The PSAMP components that help to define the physical conditions of the Puget Sound environment include the Department of Ecology's studies of rivers, streams and Puget Sound marine waters and the Department of Natural Resources' evaluation of Puget Sound's shoreline and nearshore areas.

The Pacific Ocean and Puget Sound Weather Conditions

The Pacific Ocean profoundly affects the character of Puget Sound's marine waters and the region's climate and short-term weather patterns. Waters from the Pacific Ocean enter Puget Sound directly through the Strait of Juan de Fuca and Admiralty Inlet. Changes in ocean conditions in the north Pacific lead to changes in Puget Sound water temperatures and water quality. Changes in oceanic and atmospheric conditions throughout the Pacific Ocean affect regional weather conditions.

The Pacific Ocean's Influence on the Inland Marine Waters. Waters from the Pacific Ocean are drawn into Puget Sound. Upwelling of Pacific Ocean waters draws relatively deep ocean water into the Strait of Juan de Fuca as [primarily summer] winds push surface waters away from the continent. Figure 4 shows the annual pattern of upwelling off the Washington coast: upwelling index values are positive when upwelling draws deep ocean waters toward shore and values are negative when currents push surface waters toward the coast and deep waters are displaced offshore. Upwelling is strongest during late spring, summer and early autumn.

Upwelled Pacific Ocean waters drawn into Puget Sound through estuarine circulation are rich in nutrients, relatively cold and carry low levels of dissolved oxygen (because they have been deep below the ocean surface). The introduction of water from deep in the Pacific Ocean into Puget Sound is a major determinant of marine water conditions in Puget Sound's main basin and in the Sound's many smaller passages, inlets and bays. These waters supply nutrients from the ocean that drive the productivity of the Puget Sound food web. For example, the ocean's supply of nitrogen to the Puget Sound/Georgia Basin has been estimated to be more than 10 times the input from the basin's rivers, streams and sewage discharges (Harrison et al., 1994).

The *Puget Sound Water Quality Management Plan* and threats to Puget Sound's physical environment

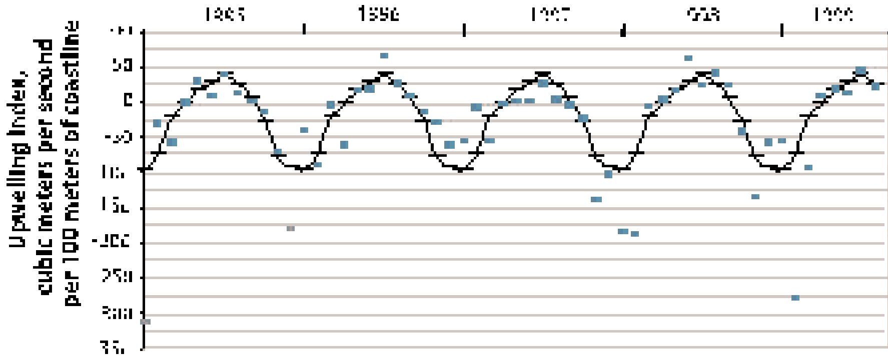
The *Puget Sound Water Quality Management Plan* addresses a number of the human-caused stresses to the Puget Sound physical environment. However, some stresses are not addressed by the Puget Sound Plan, including:

- human-induced climate change
- management of freshwater flows (except as flows are affected by stormwater management and wetlands protection and restoration).

The Puget Sound Water Quality Action Team addresses threats to the Sound's physical environment primarily through its stormwater, habitat and wetlands programs.

Figure 4. Seasonal pattern of upwelling in the Pacific Ocean at 48 degrees North latitude and 125 degrees West longitude.

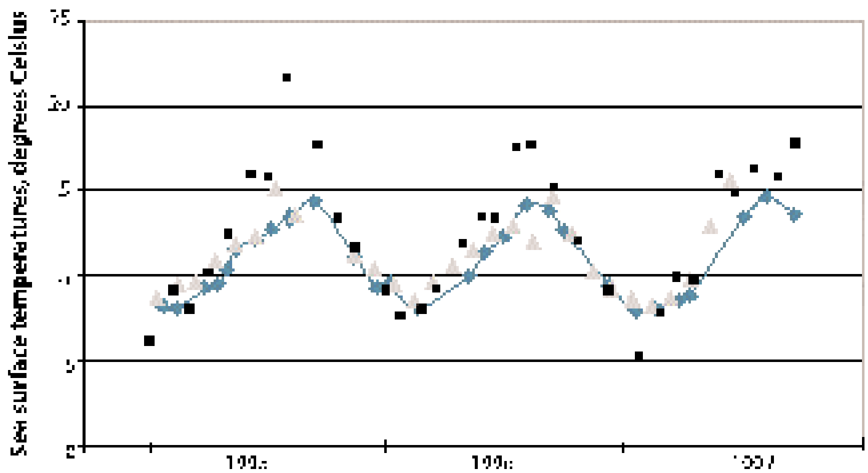
Long-term average (1946-1999)
Monthly observation



Source: National Oceanic and Atmospheric Administration's (NOAA) Pacific Fisheries Environmental Group (1999).

Figure 5. Puget Sound and Pacific Ocean sea surface temperatures, 1995-1997.

Puget Sound Main Basin
Central Budd Inlet
Pacific Ocean at Cape Elizabeth



Source: Department of Ecology and NOAA National Buoy Center data (1999).

Sea-surface temperatures measured in Puget Sound's main basin during the summer are routinely lower than temperatures offshore in the Pacific Ocean or in small, shallow, river-influenced bays and inlets such as south Puget Sound's Budd Inlet (Figure 5). The lower temperatures observed in Puget Sound's main basin compared to the open ocean indicate that colder deep waters are mixed into the surface waters of Puget Sound as a result of turbulent tidal mixing. The much warmer sea-surface temperatures in small, shallow bays such as Budd Inlet probably reflect solar heating of relatively shallow waters that are not well mixed vertically. These two patterns reflect the range of sea-surface temperatures recorded in Puget Sound: small, shallow bays and inlets have seasonally high and low sea-surface temperatures, while the deep, well-mixed basins show less variation and have generally cool temperatures.

What is the El Niño Southern Oscillation (ENSO)?

El Niño (1997-98) and La Niña (ongoing since 1998) are the extremes of the atmosphere-ocean phenomenon ENSO, which is an oscillation of atmospheric pressure and wind patterns in the equatorial Pacific Ocean. Effects from warm (El Niño) and cold (La Niña) ocean conditions off the coast of Peru are transferred through the atmosphere and ocean to the Pacific Northwest.

Puget Sound's Weather. Weather conditions in the Puget Sound basin in the late 1990s were generally warmer and wetter than normal. Air temperatures (Figure 6) and precipitation (Figure 7) records from Seattle-Tacoma International Airport (Sea-Tac) reflect these warm, wet conditions and show the influences of recent ENSO-related fluctuations on local weather conditions (NCDC, 1999).

Monthly average air temperatures at Sea-Tac from 1995 to 1998 were often higher than the long-term averages. Conversely, temperatures recorded from December 1998 to July 1999 were often lower than the long-term averages. Annual average temperatures indicate that each year from 1995 through 1998 was warmer than the long-term average. In fact, 1995 was the warmest year recorded at Sea-Tac during the period from 1961 through 1998. January and May of 1995 each had record high

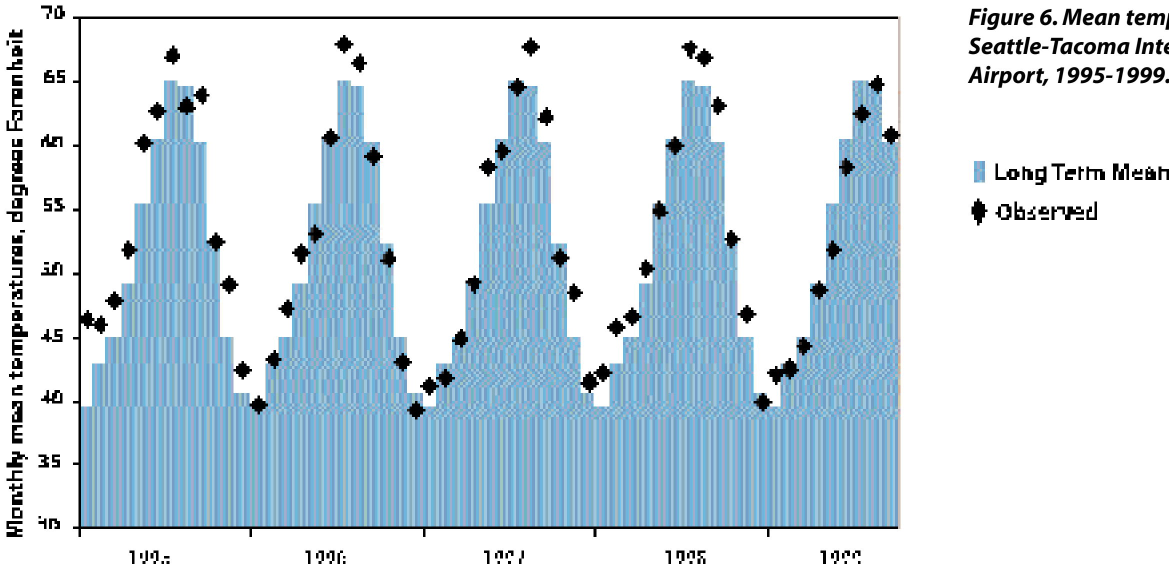


Figure 6. Mean temperatures at Seattle-Tacoma International Airport, 1995-1999.

Source: National Climatic Data Center.

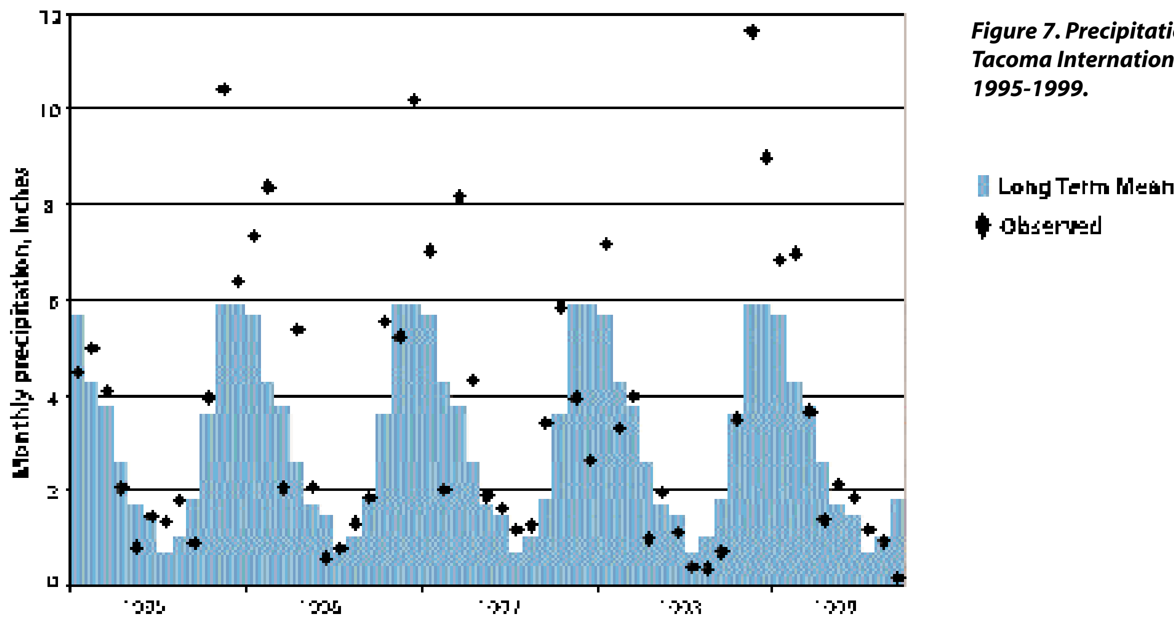


Figure 7. Precipitation at Seattle-Tacoma International Airport, 1995-1999.

Source: National Climatic Data Center.

monthly average temperatures. (No other record high monthly temperatures were set and no record low monthly temperatures were set in the period shown in Figure 6.)

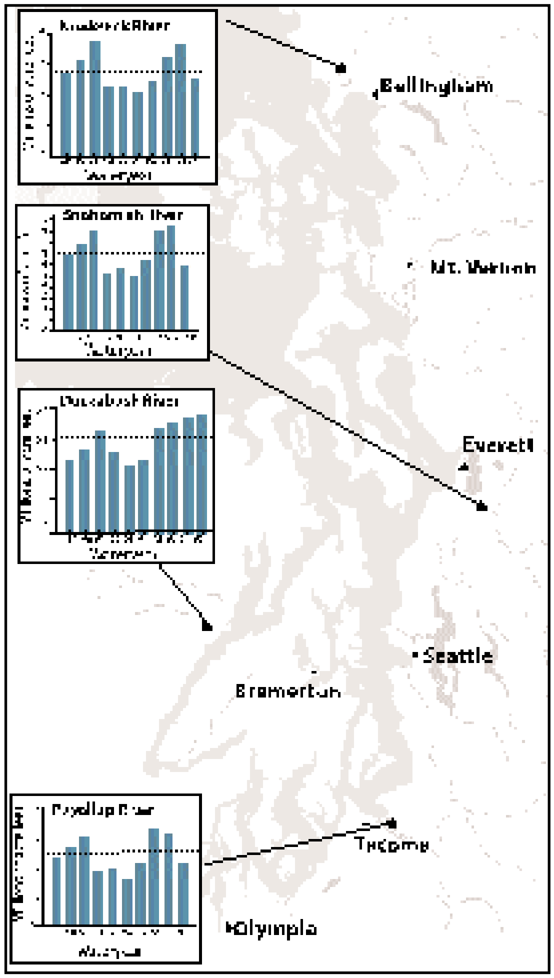
The El Niño conditions of 1997-98 appeared locally as warmer than average temperatures. Higher than average temperatures were measured in all months from November 1997 through April 1998 at Sea-Tac. Conversely, the 1998-99 La Niña conditions appeared locally as cooler than average temperatures from December 1998 through July 1999, except for January 1999.

The higher temperatures of 1995 through 1998 were accompanied by higher than average precipitation. Annual precipitation totals for these four years were all greater than the long-term average of 38.2 inches per year. A record 50.7 inches of precipitation fell at Sea-Tac in 1996. Despite the high annual total, no single month in 1996 set a monthly precipitation record. March 1997 (8.15 inches) and November 1998 (11.6 inches) set monthly records for precipitation at Sea-Tac. (For the period

Figure 8. Recent flow in four major Puget Sound basin rivers.

Observed annual flows

Long-term annual average flows



Source: Department of Ecology analysis of U.S. Geologic survey data.

presented in Figure 7, no low monthly precipitation records were set.)

The El Niño conditions of 1997-98 appeared locally as the driest winter in recent years. Figure 7 shows that peak high precipitation months were lower in 1997-98 than in the preceding two years. November and December 1997 and February 1998 were all drier than average. The La Niña of 1998-99 brought a wet winter to the Puget Sound region. Sea-Tac's record-setting November 1998 was followed by a very wet December (8.98 inches, the third wettest December on record) and a wetter than average January and February 1999. The cool temperatures recorded during this La Niña event persisted much longer into the year (July) than did the high precipitation amounts (February). In summary, the years 1997, 1998 and 1999 were very different in terms of weather conditions.

Weather can influence environmental parameters such as water quality, fish recruitment and river flow. In Puget Sound, analysis of these relationships is just beginning. Part of our current understanding about how weather conditions during El Niño and La Niña affect Puget Sound's marine waters is discussed in the sidebar: Effects of El Niño on Puget Sound water, on page 22.

Rivers and Streams—Freshwater Input to Puget Sound

Streams and rivers deliver the majority of the region's rainfall and snowmelt to Puget Sound. Delivery of water through rivers and streams is an important process that maintains instream habitat (i.e., pools, riffles and large woody debris); controls nutrient, sediment and contaminant transport; and maintains the estuarine character of Puget Sound and its many component estuaries.

Figure 8 compares annual flows for four major rivers of the Puget Sound basin with annual average flows. Total annual flow is presented by wateryear, which runs from October through September. Wateryear 1998, for example, began in October 1997 and ended in September 1998. The three rivers shown in Figure 8 that drain the eastern side of the Puget Sound basin (the Nooksack, Snohomish and Puyallup) experienced above average flows in wateryears 1996 and 1997 and below average flows for all other wateryears from 1992 through 1998. The Duckabush River, on the western side of the basin, showed a different pattern, with high flows occurring consecutively from 1995 through 1998.

Snowpack in the mountains of the Puget Sound basin

Much of the precipitation in the mountains of the Puget Sound region accumulates as snowpack. Melting snowpack through the first half of each year translates to high flows in the basin's rivers and streams that reach into the mountains. Snowpack accumulations and snowmelt are determined by a combination of temperature and precipitation.

Cold, wet conditions are most conducive to large snow accumulations. The La Niña winter of 1998-99 brought record snowfall and accumulations to the Cascade Mountains. Warm, dry conditions contribute to relatively small snow accumulations. During the warm, fairly dry El Niño winter of 1997-98, snow accumulation at Stampede Pass (in the central Cascades) was relatively low, never reaching the equivalent of 40 inches of water (National Water and Climate Center, 1999). The relatively wet years prior to 1998 brought variable snowpack accumulations to Stampede Pass, ranging from less than 40 inches of water in 1995-96 to more than 80 inches of water in 1996-97, depending on winter temperatures (above average for 1995-96 and below average for much of 1996-97).

Spring temperatures and precipitation determine the rate at which the accumulated snowpack melts and flows into rivers, streams and, ultimately, Puget Sound.

WRIA number – Basin name	Number of problem areas based on: Low instream flow	High temperature	Low dissolved oxygen	All parameters *(physical, chemical, biological)*	Total number of areas assessed
1 – Nooksack	3	14	27	63	67
2 – San Juan	0	0	0	1	5
3 – Lower Skagit/Samish	0	18	3	35	42
4 – Upper Skagit	0	3	0	3	6
5 – Stillaguamish	0	8	7	21	34
6 – Island	0	0	1	2	6
7 – Snohomish	0	7	10	24	48
8 – Cedar/Sammamish	0	4	4	47	61
9 – Duwamish/Green	0	11	11	40	51
10 – Puyallup/White	4	10	4	25	33
11 – Nisqually	0	1	1	9	10
12 – Chambers/Clover	0	4	3	12	15
13 – Deschutes	3	4	8	21	27
14 – Kennedy/Goldsborough	0	0	2	18	22
15 – Kitsap	0	4	4	64	73
16 – Skokomish/Dosewallips	1	0	0	7	8
17 – Quilcene/Snow	1	8	1	15	20
18 – Elwha/Dungeness	1	2	1	8	9
19 – Lyre/Hoko	0	7	0	7	8
Total for Puget Sound basin	13	105	87	422	545

Source: Department of Ecology unpublished data.

Table 1. Numbers of waters in various Water Resource Inventory Areas (WRIAs) identified by the Department of Ecology as impaired by poor physical conditions: low instream flow, high temperature and low dissolved oxygen.

"Impaired" indicates the body of water does not meet the applicable state water quality standard.

The 1995 through 1998 flows for the rivers draining the Cascades (the eastern side of the basin) are consistent with the precipitation data for Sea-Tac. The higher precipitation in wateryears 1996 and 1997 is reflected in the higher flows observed during those years. Precipitation at Sea-Tac does not explain the Duckabush River's high flows in wateryears 1995 and 1998. This highlights the importance of understanding meteorological and hydrologic processes on smaller scales across the large expanse of the Puget Sound basin.

The uneven distribution of precipitation through the year in the Puget Sound region combined with modification of watershed, river and stream characteristics can lead to low summer flows in some rivers and streams. River and stream flow is less variable through the year than precipitation because snowmelt and percolation into groundwater delay the runoff of much of the basin's precipitation. Nonetheless, low summer flows of rivers and streams can limit their ability to maintain aquatic life. Table 1 summarizes the distribution of Puget Sound basin waterbodies that the Department of Ecology identified in 1998 as impaired by low instream flows. The table indicates that low instream flows threatened aquatic life in the Puget Sound basin at a limited number of locations; only 13 out of 545 areas assessed were found to have low instream flows.

Instream flow is only one aspect of the physical character of river and stream water that can affect habitat quality. Other physical parameters important for maintaining high quality habitat in streams and rivers include biologically appropriate temperatures and sufficient dissolved oxygen levels. Table 1 shows that high temperatures and low dissolved oxygen concentrations were frequently responsible for water quality problems identified in the Puget Sound basin. Nearly 20 percent of the waters assessed by Ecology (105 of 545) had inappropriately high temperatures for the support of aquatic life. More than 15 percent (87 out of 545) of Puget Sound's

Identifying polluted waters - the 303(d) list

Every two years the Department of Ecology identifies Washington State's polluted waterbodies and submits a list to the U.S. Environmental Protection Agency. This list is commonly referred to as the "303(d) list" because it is required under Section 303(d) of the federal Clean Water Act. The waters enumerated in Table 1 are the "water quality limited" estuaries, lakes and streams identified by the Department of Ecology in 1998. These waters fell short of state surface water quality standards and were not expected to improve within the next two years. State water quality standards include numeric criteria used to make certain that water supports aquatic life and is safe for human uses.

rivers, streams, sloughs and bays that were assessed by Ecology had concentrations of dissolved oxygen low enough to threaten aquatic life. Additional information on marine waters affected by low dissolved oxygen is provided on pages 20 and 21.

Ecology's long-term monitoring of Puget Sound rivers provides additional information about stream temperature problems. In the Puget Sound basin, Ecology scientists collect data monthly at the 24 river monitoring stations indicated in Figure 9. Comparing state water quality standards for temperature to wateryear 1995 through 1998 monitoring results from these stations showed that measurements at these stations frequently exceeded the standard. Figure 10 shows that approximately 10 to 30 percent of the 24 river monitoring stations recorded temperatures above the

Figure 9. Ecology's core river and stream monitoring stations in the Puget Sound basin.

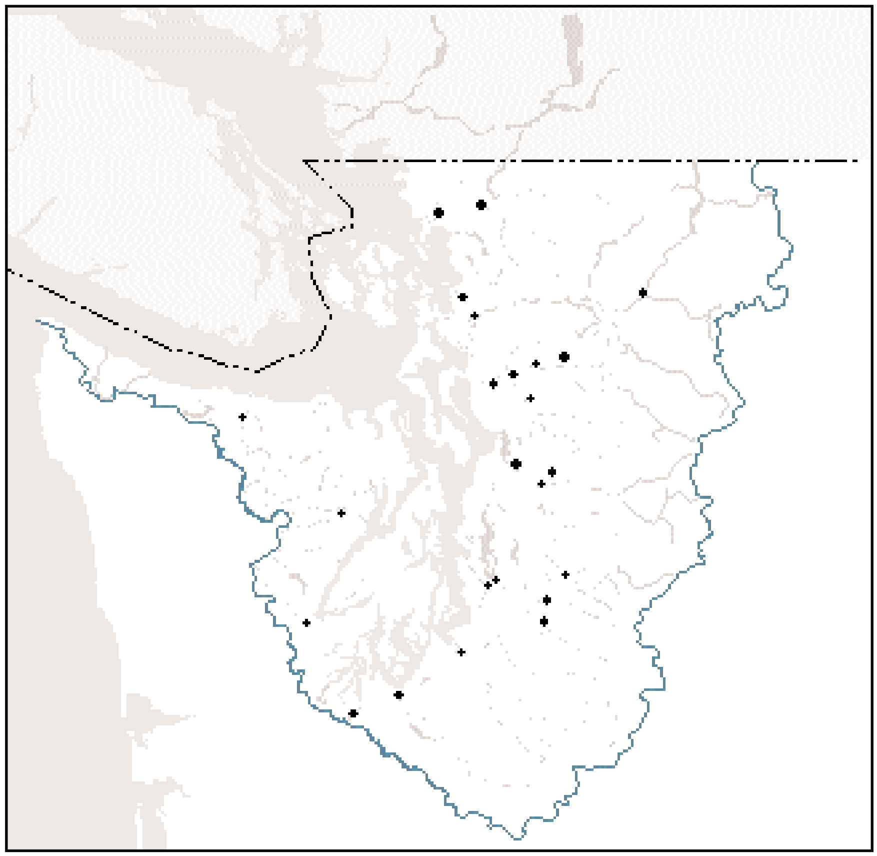
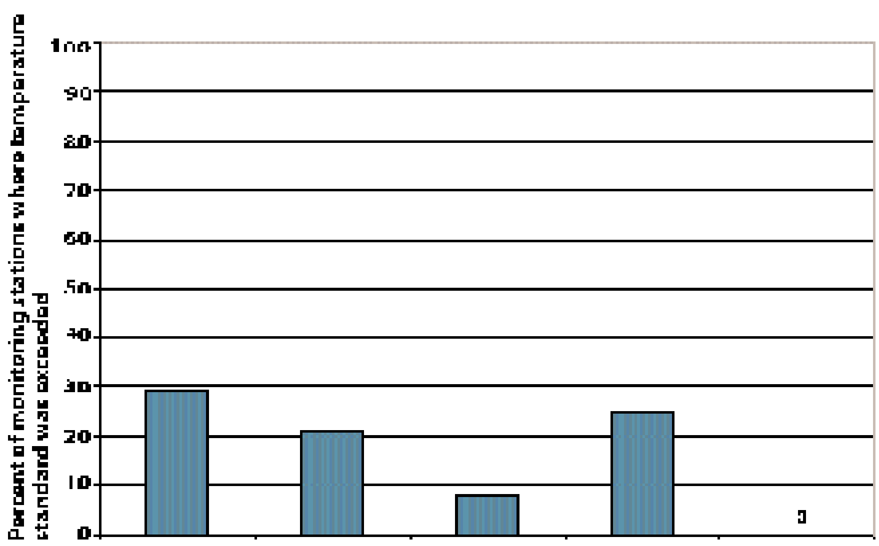


Figure 10. Percent of 24 Puget Sound river and stream monitoring stations exceeding water quality standards for temperature.



standard in wateryears 1995 through 1998. No stations exceeded the temperature standards in wateryear 1999. No trend is evident in these data. Year-to-year variations, probably related to different snowpack and resulting summer flow conditions, are quite large.

Anadromous Fish Habitat Blocked by Culverts. Rivers, streams, lakes and wetlands are all critical to the survival of migratory fish species—providing food, shelter and spawning and rearing habitat. Humans physically alter watersheds and access to these habitats by creating barriers to fish passage, such as culverts, in streams and rivers. These barriers can adversely affect the ability of wild salmon, steelhead and other anadromous salmonids to spawn and grow and can therefore cause healthy fish stocks to decline.

Scientists from the Northwest Indian Fisheries Commission have quantified the effects of known culverts on habitat availability in six Puget Sound river basins—the Cedar/Sammamish, Duwamish/Green, Puyallup/White, Quilcene/Snow, Dungeness/Elwha and Lyre/Hoko. The amount of habitat potentially available for coho salmon and the portion that is blocked by known culverts in each watershed was determined by querying the Salmon and Steelhead Habitat Inventory Assessment Program (SSHIAP) database. Figure 11 summarizes the results.

This analysis is based on coho because this species of salmon can generally penetrate farther up low elevation rivers and streams than other salmon; the analysis therefore provides a good indicator of habitat availability and condition for all salmon. For this evaluation, freshwater coho habitat is divided into two types: stream habitat (measured by length) and lake and wetland habitat (measured by area). This distinction recognizes that lakes and wetlands provide different habitat functions than stream habitat.

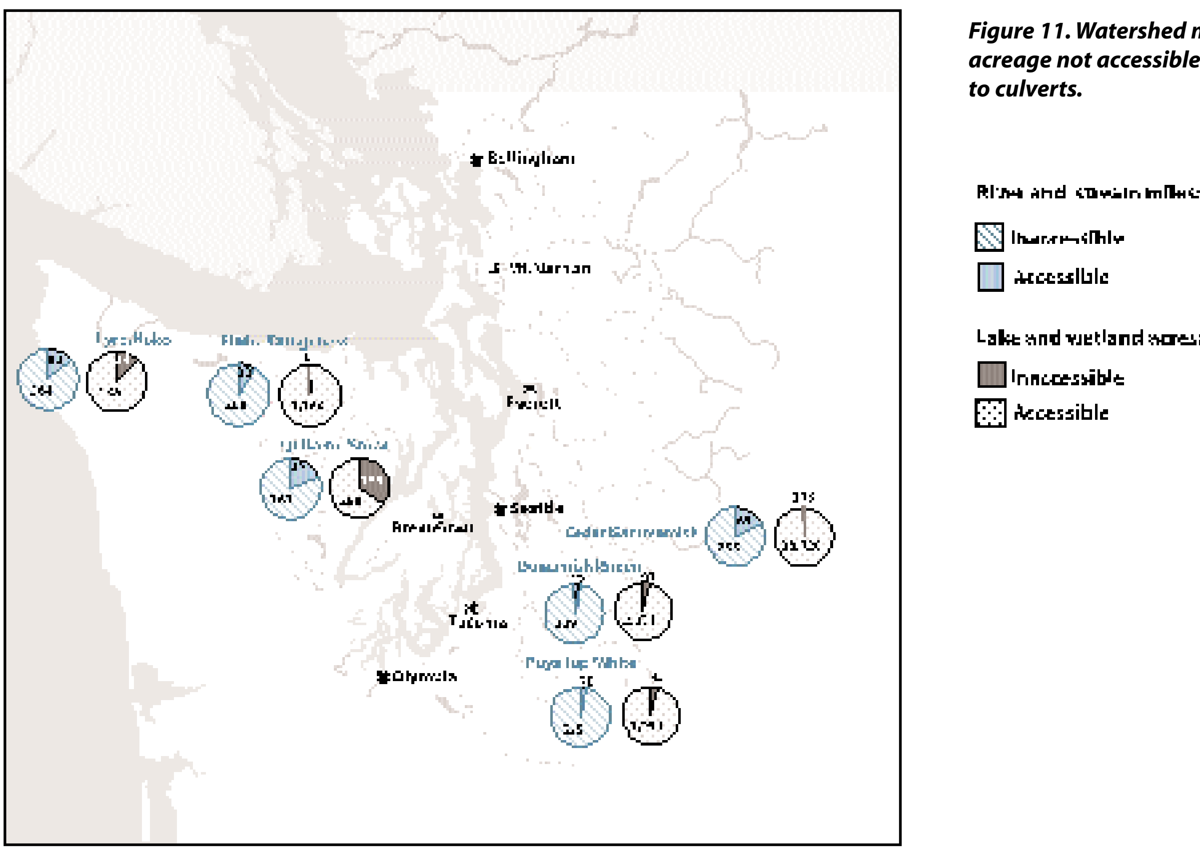
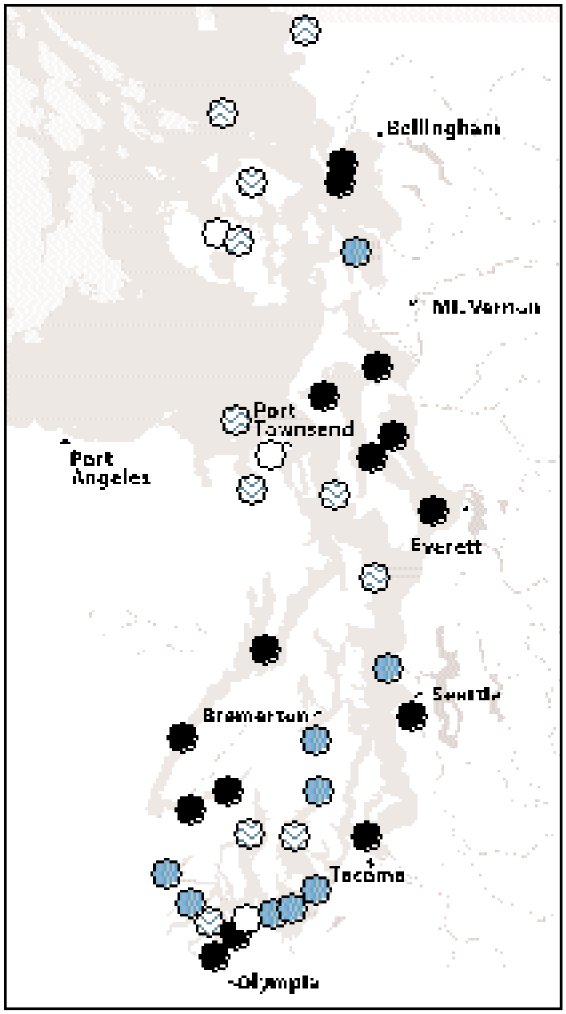


Figure 11. Watershed miles and acreage not accessible to coho due to culverts.

Source: Northwest Indian Fisheries Commission unpublished data.

Figure 12. Intensity of water column stratification in Puget Sound.



Stratification may occur in other areas of Puget Sound; not all areas of Puget Sound are monitored and stations may not reflect worst-case conditions in bays and at the heads of inlets.

The six watersheds shown in Figure 11 encompass approximately 2,100 miles of potential stream habitat for coho. Known culvert barriers block approximately 220 miles—11 percent of stream habitat. These watersheds contain nearly 35,000 acres of potential lake and wetland habitat for coho. Known culvert barriers block approximately 650 acres—or two percent—of lake and wetland habitat.

Northwest Indian Fisheries Commission scientists evaluated blockage by culverts based on a review of all available data on culvert location and condition. Dams and other physical alterations were not included in this evaluation. Estimating the total amount of habitat that is inaccessible because of culverts is difficult because a comprehensive culvert inventory does not exist for the state of Washington.

Comprehensive culvert assessments are being done in some watersheds, allowing some limitations to be addressed. For example, the Pierce County Conservation District is currently conducting an extensive culvert inventory in the Puyallup/White watershed. The number of culverts identified as a result of the new inventory is expected to be much higher than the 30 culverts previously known to exist in this watershed. These types of efforts will provide more comprehensive culvert data in the future.

Puget Sound's Marine Waters

The circulation of marine waters is an important process that partially dictates how the Puget Sound ecosystem functions and how well the ecosystem supports various habitats and species. The vertical movement of water from depth to the surface is limited when the water column is stratified, which has implications for water quality.

The Department of Ecology's ambient monitoring of the marine waters of Puget Sound has allowed scientists to describe areas of the Sound that are typically stratified. Figure 12 shows the strength of water column stratification at a number of locations throughout Puget Sound. Ecology scientists classified locations as persistently, seasonally, episodically or weakly stratified based on the types of vertical density profiles observed at sampling stations during monthly sampling from 1990 through 1997. Figure 12 updates a previous version of this map that showed the classification of sites based on data through 1995. This new version of the graphic is consistent with the older version, except in a few cases where additional data has helped to refine the characterizations.

What is stratification?

Stratification refers to the layering of water according to its density. Density is greater in cold, salty waters than in warm, fresh waters. Thus, warmer, fresher coastal waters will overlie cold, salty oceanic waters. Stratification persists when the less dense surface layer is not disrupted by winds, tides or other physical mixing. Since mixing processes and freshwater inputs are diverse in Puget Sound, a variety of stratification patterns are found.

Persistent and seasonal stratification are the most frequently observed density profile patterns in Puget Sound. Hood Canal and the bays, inlets and passages near the mouths of most large Puget Sound rivers are persistently stratified. Additional locations in south Puget Sound, around Admiralty Inlet, and in the San Juan Islands and Strait of Georgia are seasonally stratified. The widespread occurrence of density stratification and the persistence of stratification observed near river mouths reflect the importance of freshwater input to the character of Puget Sound's marine waters.

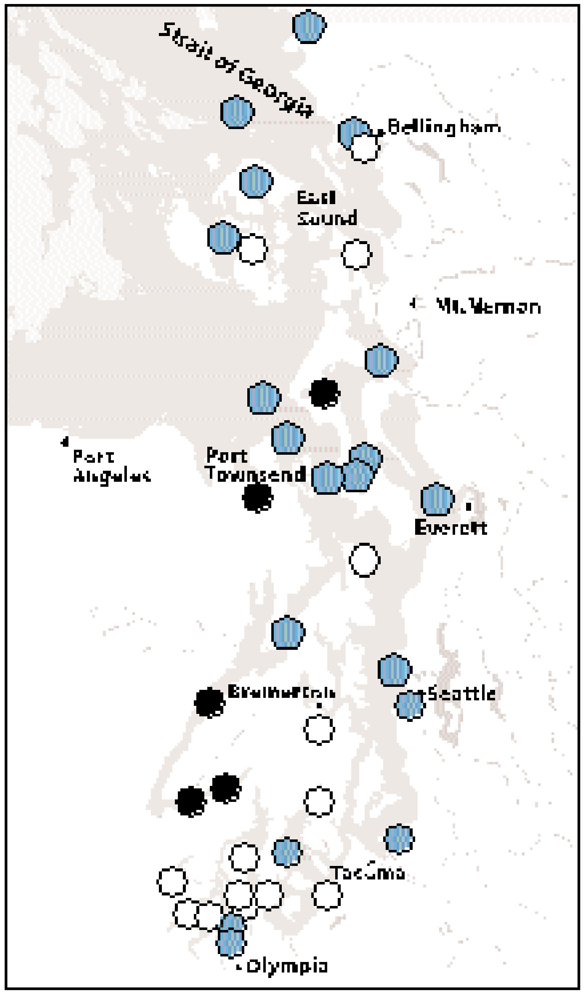
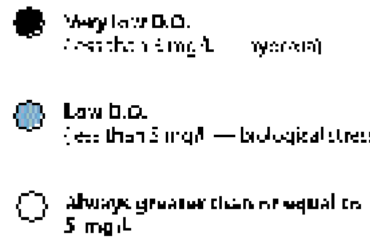


Figure 13. Areas of low dissolved oxygen (D.O.) in Puget Sound waters, wateryears 1996 and 1997.



Low dissolved oxygen (D.O.) may occur in other areas of Puget Sound; not all areas of Puget Sound were monitored in 1996 and 1997, and stations may not reflect worst-case conditions in bays and at the head of inlets.

Persistent water column stratification can increase the severity of a waterbody's response to actions that degrade water quality. Stratified waters keep substances contained within a smaller area than if the water column was more fully mixed. For instance, chemical or biological contaminants discharged into the surface layer of a stratified water body will stay relatively concentrated instead of being dispersed throughout the entire water column.

Another impact of stratification is that persistent stratification will contribute to the depletion of dissolved oxygen from bottom waters. In areas with strong stratification, phytoplankton populations can grow rapidly—as soon as light levels increase in spring—because the algae cells are not dispersed too rapidly from well-lit surface waters. In the absence of mixing, phytoplankton cells and organic matter will ultimately settle into bottom waters where decomposition of the organic matter consumes dissolved oxygen. In a stratified water column, bottom waters do not circulate to the water surface; therefore, they are not replenished with dissolved oxygen through contact with the atmosphere. If stratification persists, the bottom waters can become depleted of oxygen.

Figure 13 shows locations in Puget Sound where Ecology scientists measured low concentrations of dissolved oxygen in bottom waters during wateryears 1996 and 1997. As designated in the figure, a concentration of 5 mg/L of dissolved oxygen is generally considered the level at which biological stress may begin to occur. Less than 3 mg/L of dissolved oxygen results in hypoxia, a condition marked by low oxygen levels that can have detrimental effects on many marine organisms. The patterns shown in Figure 13 are very similar to those shown for 1990 to 1995 in the 1998 Puget Sound Update. As expected, the areas with very low dissolved oxygen (less than

Effects of El Niño on Puget Sound water

El Niño events in 1991-92 and 1997-98 raised sea-surface temperatures in the Pacific Ocean off the Washington coast. Ecology's marine water monitoring showed that Puget Sound water temperatures were also warmer during these events. Sea-surface temperatures in Puget Sound were one to three degrees Celsius warmer than the average conditions for Puget Sound measured from 1990 through 1998.

In the Pacific Northwest, El Niño winters are typically drier than normal. Reduced precipitation results in lower stream flows, which, in turn, leads to increased salinity in marine waters. Ecology data show that Puget Sound waters were more saline than normal during the 1991-92 El Niño, when precipitation was relatively low. During the relatively dry 1997-98 El Niño, Puget Sound salinity values were at average levels. The reduced precipitation during this latest El Niño apparently caused Puget Sound salinity values to rebound from the fairly low levels recorded during the relatively wet years from 1995 to 1997.

Monitoring data do not indicate how, if at all, shifts in temperature and salinity observed during El Niño events may affect the Puget Sound ecosystem. Further investigation is needed to determine if ENSO-related variations affect marine organisms, alter seawater density sufficiently to affect marine water circulation, or affect the timing or character of phytoplankton blooms.

3 mg/L) have persistent or seasonal stratification and are located towards the end of long, narrow bays (Hood Canal, Penn Cove, Discovery Bay). Other areas with low dissolved oxygen (less than 5 mg/L) include a mix of stratified waters and areas receiving upwelled deep waters that have naturally low dissolved oxygen levels.

The low dissolved oxygen in Admiralty Inlet, Puget Sound's main basin and the waters of nearby San Juan Island reflects the natural input of seasonally upwelled oceanic waters entering Puget Sound. Whether humans are affecting the magnitude of the low dissolved oxygen concentrations in some of the stratified bays such as Hood Canal, Penn Cove and Discovery Bay is not easy to assess. Ecology scientists are currently investigating dissolved oxygen dynamics in Hood Canal.

While the majority of the information in Figure 13 is similar to that presented in the 1998 Update, there are some differences. First, some areas were not previously monitored. Newly monitored areas showing low dissolved oxygen were Discovery Bay, Drayton Harbor and Friday Harbor. Second, some areas show different results than before; interannual variation should be expected because stratification and algae growth are highly dependent on weather. During 1996 and 1997, for instance, dissolved oxygen measurements below 3 mg/L were not measured in Budd Inlet and East Sound (Orcas Island) as they had been earlier in the 1990s. At the Central Hood Canal station, however, more severe conditions (less than 3 mg/L) were observed in 1996 and 1997 than earlier in the 1990s.

New observations of dissolved oxygen concentrations below 5 mg/L were recorded at Bellingham Bay, inner Admiralty Inlet, Commencement Bay, Carr Inlet and West Point off Seattle. In some of the latter cases, the dissolved oxygen concentrations were only slightly below 5 mg/L (<5 percent) and are therefore probably not significant. Longer data records will help to identify whether the observed interannual variation co-varies with weather cycles or whether any trends exist.

Puget Sound's Shoreline

Development has substantially altered Puget Sound's shoreline, leading to losses of natural habitat—especially in nearshore areas—and extensive changes in nearshore circulation and sediment transport processes. Habitat loss is a major threat to biodiversity and ecosystem health; it is the single most common factor associated with the listing of endangered or threatened species nationwide (Wilcove et al., 1998). Habitat loss in Puget Sound's nearshore areas is of particular concern because shallow subtidal and intertidal habitats are some of the most productive components of our ecosystem, and many birds, fish, invertebrates and mammals rely on these habitats during critical life stages. For this reason, the British Columbia/Washington Marine Science Panel made protecting estuarine habitat its highest priority recommendation for ecosystem health (BC/WA Marine Science Panel, 1994).

It is difficult to precisely quantify the extent of nearshore habitat lost due to human activities. However, information is available that highlights the magnitude of these losses:

- Estuarine habitat is generally considered to be the habitat type in the Puget Sound region that is most severely affected by humans. More than 50 percent of tidal flats and intertidal areas in major embayments has been lost since 1850 (Bortleson et al., 1980). Losses have been significantly higher in urbanized areas. For example, Commencement Bay has lost more than 99 percent of its marsh habitat and 95 percent of its intertidal mudflats (U.S. Army Corps of Engineers et al., 1993).

- The quality of remaining estuarine habitat in the Puget Sound region is commonly degraded. As discussed on page 50, approximately 5,700 acres in Puget Sound's urban bays have been identified as having sediment contaminant concentrations that do not meet the state's sediment quality standards. The highest concentrations of contaminants occur in the sediments of urbanized bays, such as Elliott Bay, Commencement Bay, Budd Inlet and Sinclair Inlet. Water quality is impaired in 65 percent of Washington's estuaries (Butkus, 1997).
- Nearshore areas throughout Puget Sound have been altered by development. Humans modify the shoreline and destroy natural habitat directly through construction of bulkheads and other structures and through activities such as filling and dredging. Habitat loss also occurs indirectly through alteration of nearshore processes like wave energy and sediment transport. One common impact of nearshore habitat modification or destruction is beach erosion, which is caused by loss of sediment supply. Another impact is increased runoff. In addition to specific local impacts, the extent of shoreline modification also indicates the intensity of a wide range of human activities affecting nearshore areas. Scientists with the Department of Natural Resources estimate that humans have modified one-third of Puget Sound's shoreline (Puget Sound Water Quality Action Team, 1998). The main basin of Puget Sound is the most intensively modified region of the Sound; more than half of its shoreline has been altered. Other regions are significantly less altered; approximately 20 percent of the shorelines are modified in the region that includes the San Juan Islands and Strait of Juan de Fuca.

Rapid Mapping of Shoreline Using the ShoreZone Inventory. Consistent information about shoreline habitat is needed to characterize the abundance and distribution of different habitats and their general health. To fill this need, staff of the Nearshore Habitat Program at the Department of Natural Resources are completing a rapid statewide inventory of saltwater shorelines using the ShoreZone Mapping System. The ShoreZone inventory provides regional information about spatial patterns in the nearshore environment. It is intended to augment, rather than replace, more detailed habitat studies.

The ShoreZone Mapping System allows scientists to rapidly survey intertidal areas via helicopter. During the fly-over, a video image of the shoreline is recorded with accompanying audio descriptions from a geomorphologist and a biologist. These recordings are then translated to geographic data and maps that describe the physical and biological characteristics of the shoreline. The data include approximately 50 parameters that describe shoreline geomorphology, vegetation and human development features.

Natural Resources will complete data analysis and make the statewide ShoreZone inventory available in late 2000. Preliminary data analysis has been completed for the eastern side of Puget Sound's main basin. This region contains some of the most extensively developed shorelines in Puget Sound, including Seattle and Tacoma. Results for four of the parameters inventoried are shown in Figure 14 (page 24). These examples from the ShoreZone mapping inventory provide the following information:

- Intertidal areas of the eastern side of Puget Sound's main basin have been extensively modified; 79 percent of the shoreline has

What is nearshore habitat?

Nearshore habitat includes the area from 65 feet below mean low water to 200 feet upland of the ordinary high water mark. This area generally encompasses several of the following habitats: bluffs, beaches, marshes, riparian vegetation, sandflats, mudflats, rock and gravel habitats, unvegetated subtidal areas, kelp beds, intertidal algae and eelgrass beds.

some type of modification (e.g., bulkheads, docks, piers) in either the intertidal or backshore zones. Along more than one-quarter of the shoreline, the predominant substrate throughout the intertidal zone is man-made.

- The abundance and distribution of different shoreline types in this area reflects both natural patterns in the main basin and historical development trends. The natural shoreline is primarily composed of narrow sand and gravel beaches; rocky intertidal habitat is rare.

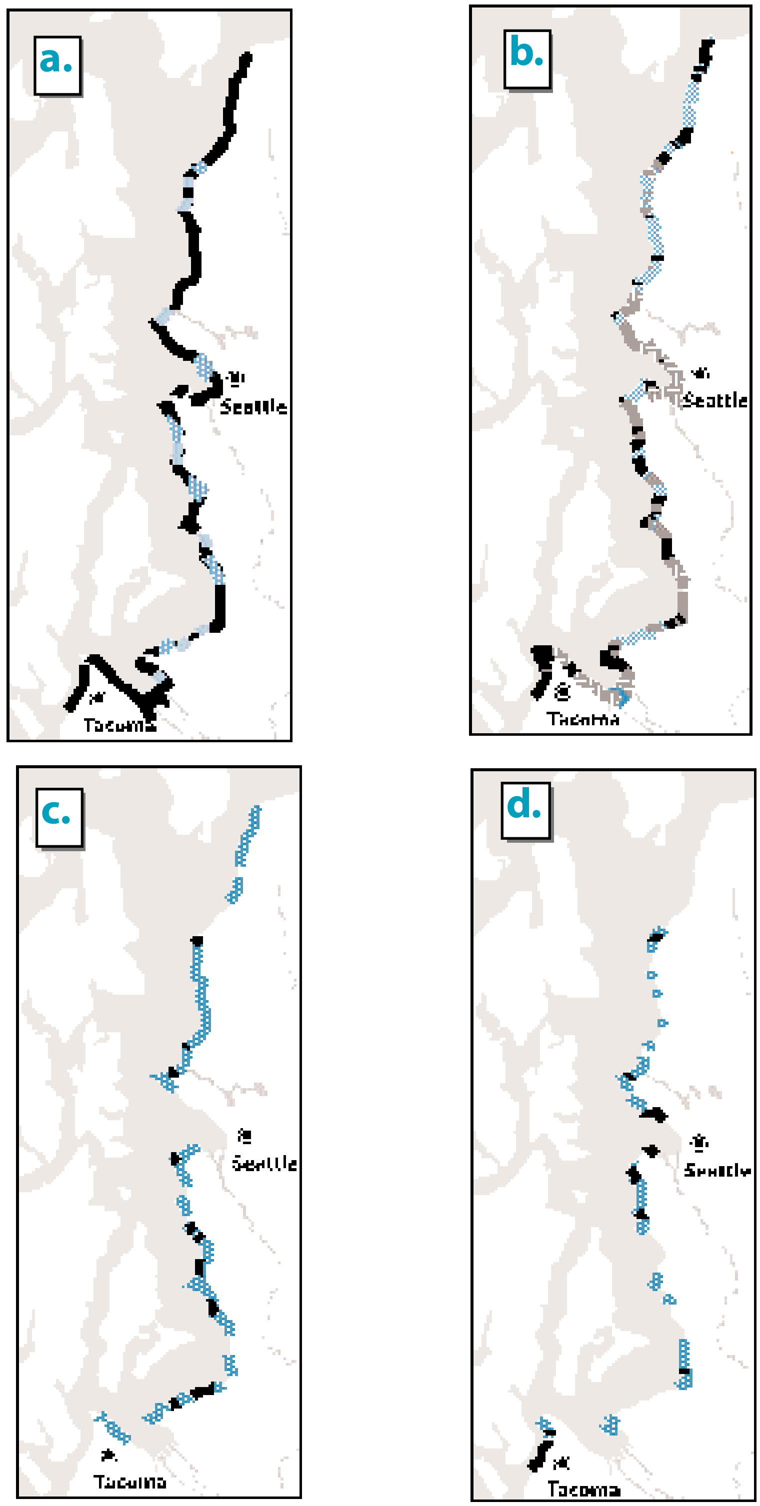


Figure 14. ShoreZone inventory of the eastern shore of Puget Sound's central basin.

a. Shoreline modification: 79%
- 5-35% modified
- 36-65% modified
- 66-100% modified

b. Shoreline type
- sand & gravel flat (18%)
- sand & gravel beach (24%)
- sand beach (19%)
- sand & mud flat (12%)
- man-made (27%)

c. Eelgrass: 48%
- continuous (8%)
- patchy (40%)

d. Sargassum muticum: 27%
- continuous (7%)
- patchy (20%)

Analyzing habitat trends across the British Columbia/Washington border

In addition to describing spatial patterns of shoreline characteristics within Puget Sound, the ShoreZone Mapping System will be a useful tool for analyzing trends in habitat across the international border. The system was originally designed in British Columbia and is being used to map provincial shorelines. A joint protocol is being defined by the Washington Department of Natural Resources' Nearshore Habitat Program and the British Columbia Land Use Coordination Office.

Tidal flats comprise only 12 percent of the shoreline today, reflecting the historic loss of estuarine habitat in urbanized embayments.

- Eelgrass *(Zostera marina)* provides important habitat for salmon, marine fish, birds and other wildlife and occurs throughout the study area. Almost one-half of the shoreline has patchy or continuous eelgrass beds. Because of the recognized ecological importance of eelgrass beds, these areas are protected by state policies. It is not known how the distribution of eelgrass has changed along this shoreline over time. Temporal change in the extent of eelgrass is an important topic for future monitoring.
- *Sargassum muticum* is a non-native algae that is established throughout Puget Sound. Its distribution and potential impact on the local ecosystem are not well understood. The ShoreZone inventory provides preliminary information that *Sargassum* beds are extensive along the study area; 27 percent of this shoreline has patchy or continuous beds.

Detailed Inventory of Intertidal Shoreline Characteristics. Department of Natural Resources scientists complete detailed shoreline surveys in focus areas as resources allow. Inventory results are distributed on CD-ROM to assist in land-use planning and to improve understanding of linkages between habitats and species. In 1999, Natural Resources' Nearshore Habitat Program released inventory information for 230 miles of shoreline in Skagit County and northern Island County.

The habitat inventory describes physical characteristics that most strongly affect the distribution of shoreline plants and animals. Intertidal habitats were classified based on substrate, elevation, human modification and energy regime according to *A Marine and Estuarine Habitat Classification System for Washington State* (Dethier, 1990).

Washington State has some of the most diverse shoreline habitats in the world. The inventory illustrates the range in habitat types, from narrow rock ledges along Deception Pass to broad mud and sand flats in Cornet Bay. (See Figure 15 in the color section on page 112.) Mixed fine and sand habitats were the most abundant in terms of acres inventoried (Table 2). These types of habitats support important vegetation communities such as eelgrass meadows and salt marshes. Habitats composed of larger substrates (e.g., gravel, cobble) are less abundant in terms of overall acreage because they tend to be narrower, but they are the most common in terms of total shoreline miles.

A significant portion of natural habitat in the Skagit County study area has been lost through human conversion of upper intertidal and backshore areas to man-made substrate (Figure 16, page 26). The inventory indicates that 34 percent of the shoreline has been modified. Most of this is due to agricultural diking practices in this county.

In addition to describing physical characteristics, the habitat inventory delineates intertidal and canopy-forming vegetation. This data set is discussed in the

Substrate Type	Acres	Percent
artificial	91	< 1
bedrock	220	< 1
boulders	100	< 1
cobble	10	< 0.1
gravel	240	< 1
hardpan	0.3	< 0.1
mixed coarse	880	3.0
mixed fine	10,000	34
mud	4,400	15
organic	410	1.4
sand	13,000	44
Total	**29,351.3**	**100**

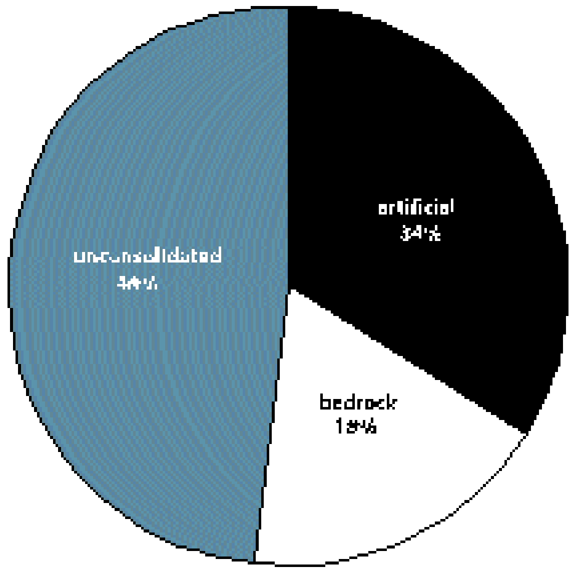
Table 2. Areal extent of intertidal substrate types for Skagit County study area.

ShoreZone Inventory results on Whidbey Island shoreline alteration

Department of Natural Resources scientists queried the ShoreZone inventory data to develop an independent estimate of shoreline modification on Whidbey Island. This analysis showed that just over 20 percent of the island's 155 miles of shoreline are modified in some way. The Beach Watchers' estimate of just over 22 percent for 125 miles of the Whidbey shoreline agrees with this ShoreZone result. The citizen monitoring protocol developed and implemented by Island County/WSU Beach Watchers would provide a direct means of monitoring changes over time in shoreline alteration for selected areas of Puget Sound.

Figure 16. Substrate type at the extreme high water line for Skagit County study area.

Refer to Table 2 (page 25), for examples of unconsolidated substrate, which includes everything but artificial substrate and bedrock. (Unconsolidated means that the substrate moves and does not stay in one large block.)



Biological Resources section of this report (page 81).

Beach Watchers' Assessment of Shoreline Alteration on Whidbey Island. Bulkheads, seawalls, piers, docks, launch ramps, jetties, groins and other structures have hardened over 22 percent of the Whidbey Island shoreline (Island County/Washington State University (WSU) Beach Watchers, 1999). From April to September 1999, volunteers with Island County/WSU Beach Watchers measured the extent of shoreline armoring on approximately 125 miles of Whidbey Island's 155-mile shoreline. The survey used a citizen monitoring protocol that was developed by Beach Watchers and other Puget Sound region citizen monitoring groups (Island County/WSU Beach Watchers 1999). Volunteers measured shoreline structures and unaltered lengths of beach as they walked the high tide line with a measuring wheel. Because surveys were not completed for about 30 miles of Whidbey Island, Beach Watchers' estimate of the proportion of Whidbey Island shoreline that is altered may change slightly when the entire shoreline has been surveyed.

Citizen Shoreline Inventory of King, Pierce and Thurston Counties. The Citizen Shoreline Inventory (CSI) was developed to evaluate the relationship between shoreline development activities and the health of adjacent nearshore habitats in Puget Sound. CSI is a joint effort between People for Puget Sound and Adopt a Beach. Data from CSI are available at http://www.pugetsound.org/csi.

After two years of data collection, scientists at People for Puget Sound analyzed the CSI database to evaluate potential indicators with which to assess the health of Puget Sound's nearshore environment. Data collected in the summer of 1998 from 163 150-foot sections of shoreline in King, Pierce and Thurston counties were analyzed to investigate relationships between habitat characteristics and shoreline alteration (Figure 17).

Shoreline alteration (armoring) was observed at 37 percent of the 163 sections. Eelgrass was more commonly observed in unaltered sections than in altered sections. In addition, fine sediments that provide habitat for many intertidal organisms, including small invertebrates (which are the primary prey for juvenile salmon), were less common in altered areas, with 13 percent of armored sections having cobble as the dominant low intertidal substrate. In contrast, only one percent of unarmored sections had cobble as the dominant substrate. The association between alteration and the presence of cobble substrate may indicate the loss of fine sediment habitat where the shoreline is armored.

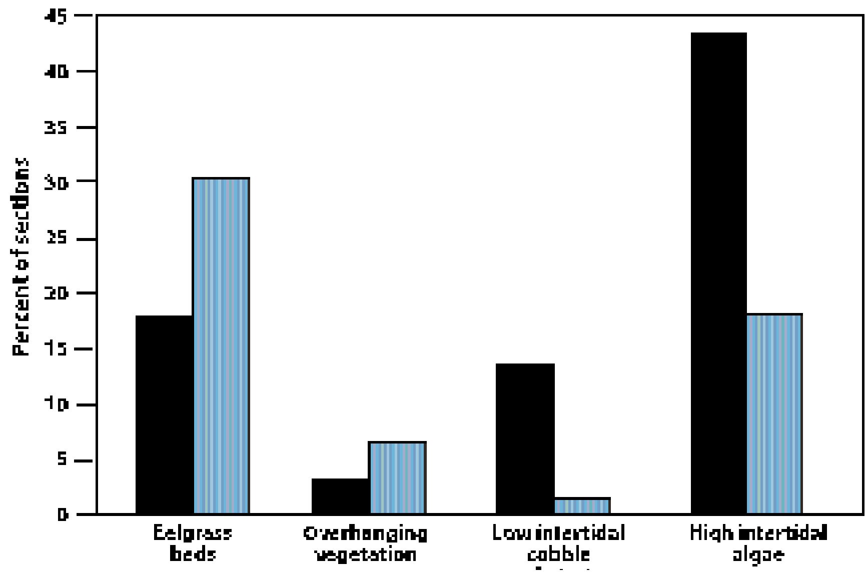
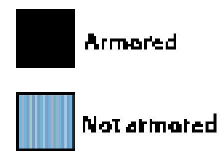


Figure 17. Citizen Shoreline Inventory habitat parameters for armored and unarmored shoreline sections in King, Pierce and Thurston counties, summer 1998.



Source: People for Puget Sound's unpublished analysis of Citizen Shoreline Inventory data.

Acting on the Findings

The information presented in this chapter suggests a number of recommendations for further scientific study and resource management:

- The Department of Ecology should continue (and emphasize) its efforts to develop clean-up plans (also known as total maximum daily loads or TMDLs) for rivers and streams that are impaired by high temperatures and low instream flow. These plans should provide the technical basis for watershed and riparian area improvements that will lead to water quality improvements.
- Local governments and the state should work with land owners to develop more information on culverts and other blockages to salmon habitat. Comprehensive culvert inventories, such as the one currently being conducted by the Pierce County Conservation District for the Puyallup/White watershed, are needed for all watersheds in the Puget Sound basin in order to assess availability of salmon habitat at a time when several salmon species are at risk.
- Local, state and federal agency staff should consider the implications of water column stratification in many of Puget Sound's inlets and bays as they evaluate the effects of discharges to the Sound.
- Ecology should track trends in dissolved oxygen at all of its marine monitoring stations and it should conduct intensive investigative surveys at any locations with decreasing dissolved oxygen levels.
- After Department of Natural Resources scientists complete the ShoreZone inventory, this information should be disseminated to shoreline planners, state agency and tribal staff, and others who should use the inventory in resource management and permitting decisions. Alternatives to beach hardening should be considered.
- State agencies and local governments should make use of nearshore monitoring data collected by citizen monitoring groups to augment data from other sources. Citizen monitoring should be encouraged as a means of developing data needed for shoreline and nearshore resource management decisions.